

Search for CP Violation in Hyperon Decays

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XXIV Physics in Collision

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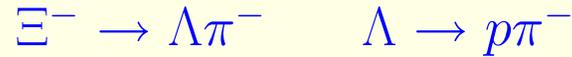
Why Search for CP Violation in Hyperon Decays?

- After 40 years of intense experimental effort — and many beautiful experiments — we still know little about CP violation: the origin of CP violation remains unknown and there is little hard evidence that it is explained by the Standard Model.
- CP violation is too important, and experimental evidence is too meagre, not to examine every possible manifestation of the effect.
- Hyperons are sensitive to sources of CP violation that are not probed in other systems.
- These sources are experimentally accessible.
- The price is modest:
 - No new accelerators needed.
 - Apparatus is modest in scope and cost.
- Beyond-the-standard-model physics almost invariably predicts large new sources of CP violation.

“We are willing to stake our reputation on the prediction that dedicated and comprehensive studies of CP violation will reveal the presence of New Physics.”

Bigi and Sanda, CP Violation

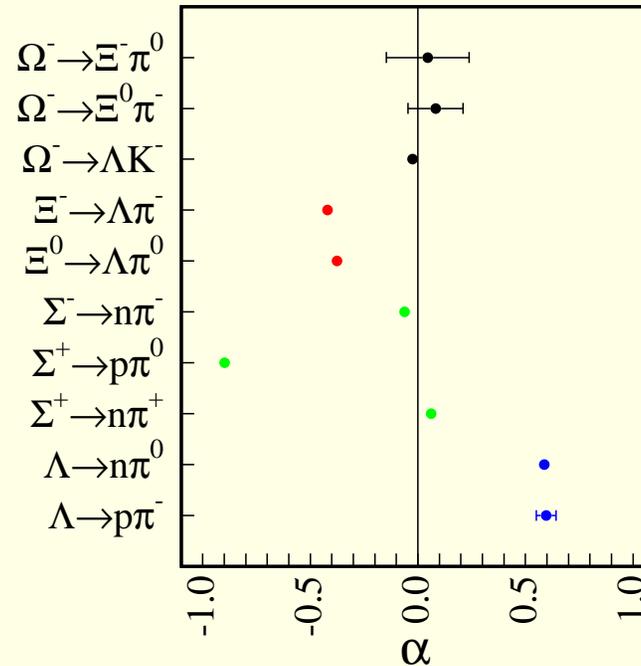
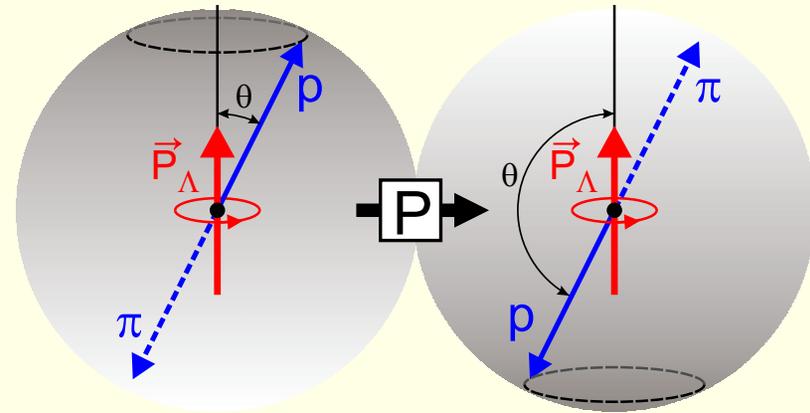
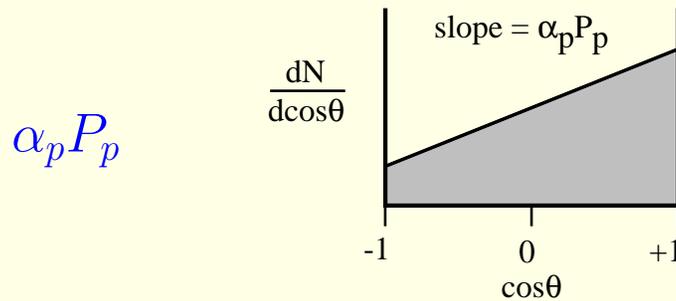
Short Primer on Nonleptonic Hyperon Decays



- **Decay violates parity:** angular distribution of daughter baryon is not isotropic (if parent is polarized)

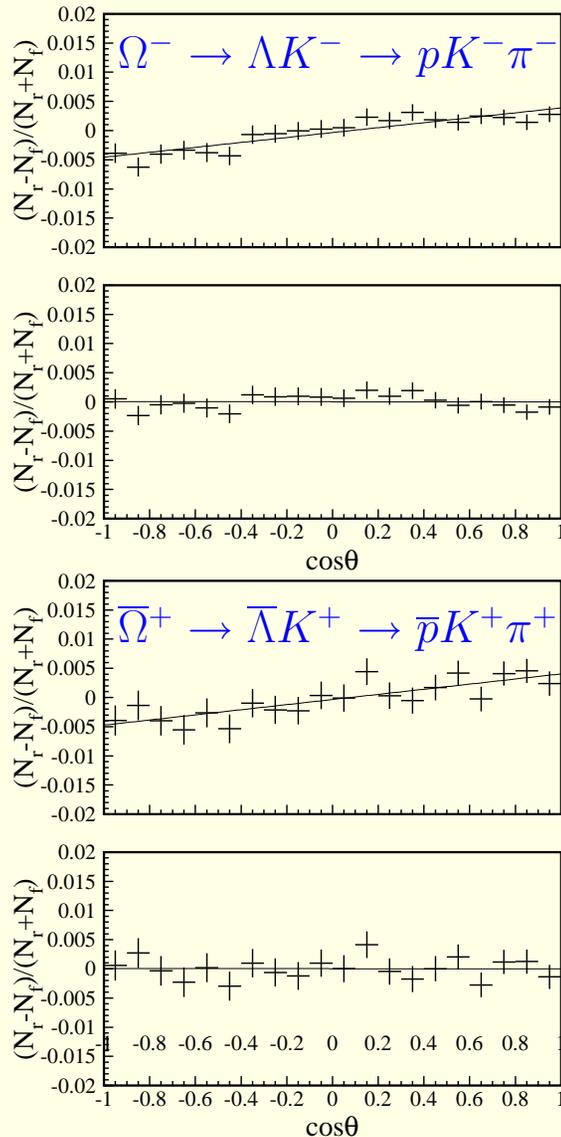
$$\frac{dP}{d\cos\theta} = \frac{1}{2}(1 + \alpha_p P_p \cos\theta)$$

- The magnitude of the parity violation is given by α_p
- The slope of the daughter baryon $\cos\theta$ distribution is given by:



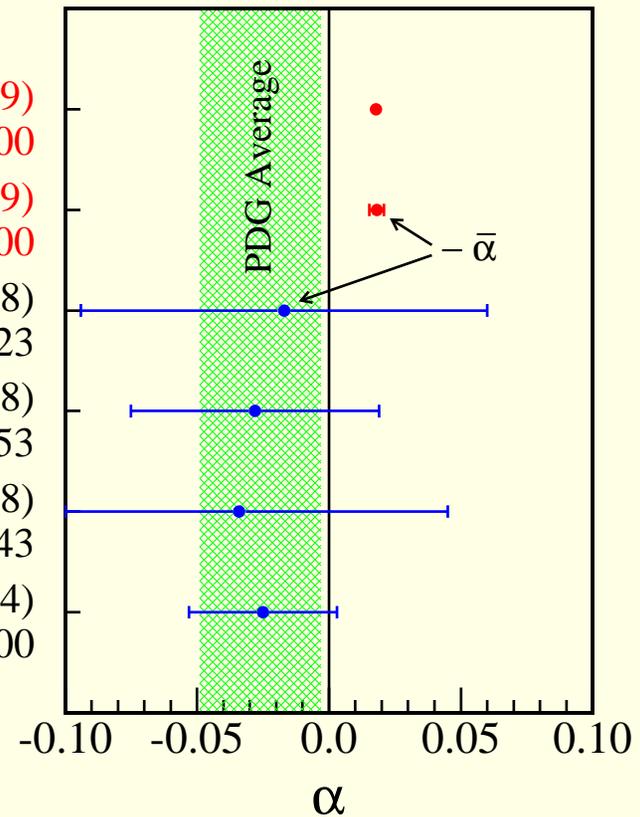
- Hyperon alpha parameters large!

Preliminary Measurement of α_Ω and $\bar{\alpha}_\Omega$ in $\Omega^- \rightarrow \Lambda K^-$ Decays



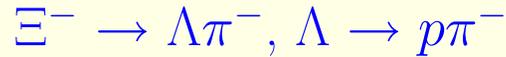
1999 : $\alpha_\Omega = [1.78 \pm 0.19(\text{stat}) \pm 0.10(\text{syst})] \times 10^{-2}$
 1999 : $\bar{\alpha}_\Omega = [-1.81 \pm 0.28(\text{stat})] \times 10^{-2}$

HyperCP (1999)
 4,500,000
 HyperCP (1999)
 1,900,000
 FNAL-756 (1998)
 1823
 FNAL-756 (1998)
 6953
 FNAL-620 (1988)
 1743
 CERN (1984)
 12,000



- First evidence of parity violation in Ω^- decays.
- Can search for CP violation in $\Omega^-/\bar{\Omega}^+$ decays.

Short Primer on Nonleptonic Hyperon Decays



Daughter Λ baryon is polarized

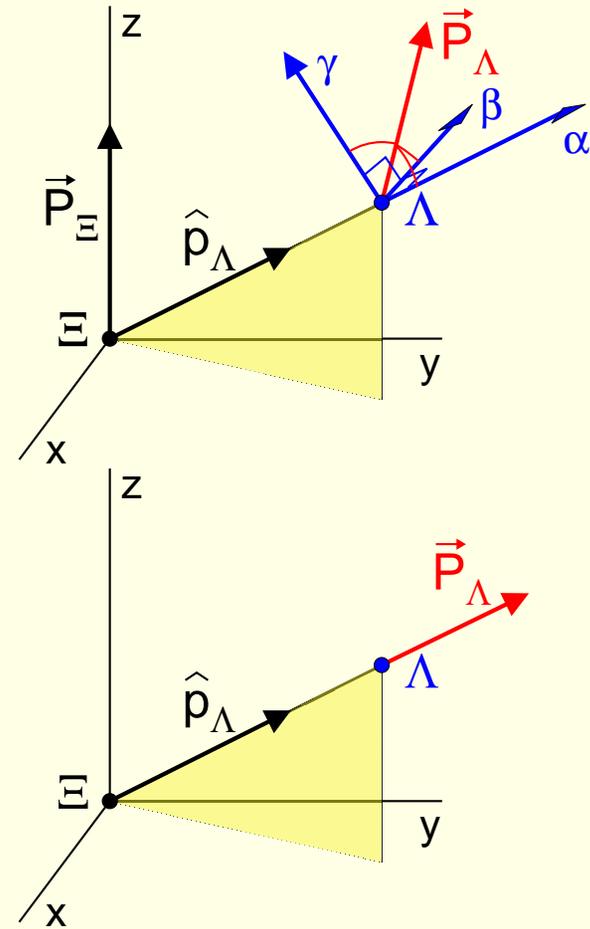
$$\vec{P}_\Lambda = \frac{(\alpha_\Xi + \vec{P}_\Xi \cdot \hat{p}_\Lambda)\hat{p}_\Lambda + \beta_\Xi(\vec{P}_\Xi \times \hat{p}_\Lambda) + \gamma_\Xi(\hat{p}_\Lambda \times (\vec{P}_\Xi \times \hat{p}_\Lambda))}{(1 + \alpha_\Xi \vec{P}_\Xi \cdot \hat{p}_\Lambda)}$$

where:

$$\alpha = \frac{2\text{Re}(S^*P)}{|S|^2 + |P|^2} \quad \beta = \frac{2\text{Im}(S^*P)}{|S|^2 + |P|^2} \quad \gamma = \frac{|S|^2 - |P|^2}{|S|^2 + |P|^2}$$

If parent Ξ^- is **unpolarized**:

$$\vec{P}_\Lambda = \alpha_\Xi \hat{p}_\Lambda$$

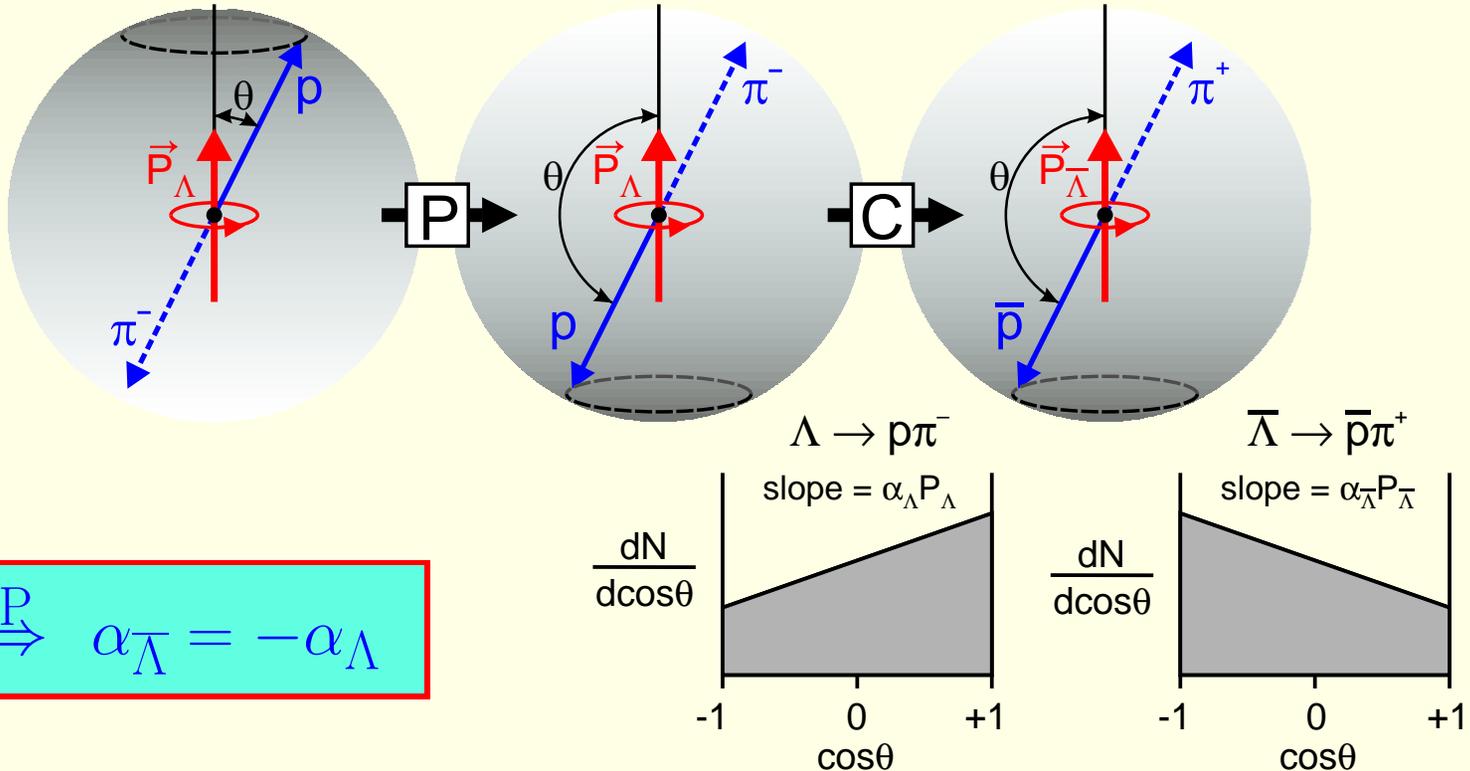


How to Search for CP Violation in Λ Decays

Due to parity violation the proton likes to go in the direction of the Λ spin:

$$\Lambda \rightarrow p\pi^-: \quad \frac{dN(p)}{d\cos\theta} = \frac{N_0}{2}(1 + \alpha_\Lambda P_\Lambda \cos\theta) \quad \alpha = \frac{2\text{Re}(S^*P)}{|S|^2 + |P|^2} = 0.642$$

Under CP the antiproton likes to go in the direction **opposite** to the $\bar{\Lambda}$ spin:



Problem: The $\Lambda/\bar{\Lambda}$ polarizations have to be precisely known to extract $\alpha_\Lambda/\bar{\alpha}_\Lambda$

Three ingredients needed to have an experiment

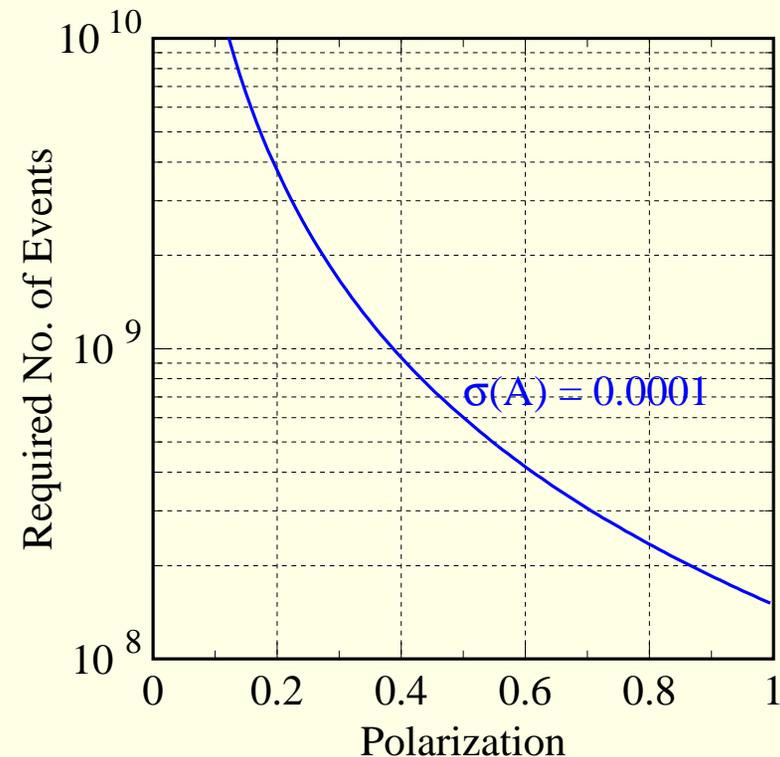
1. A way of producing $\Lambda, \bar{\Lambda}$, or $\Xi^-, \bar{\Xi}^+$ with either:
 - the same polarization
 - polarizations known to the level of the desired precision in the asymmetry measurement
2. Lots of events with large polarization:

$$\sigma(A) = \frac{1}{P} \sqrt{\frac{3}{2N}}$$

$$A = \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}}$$

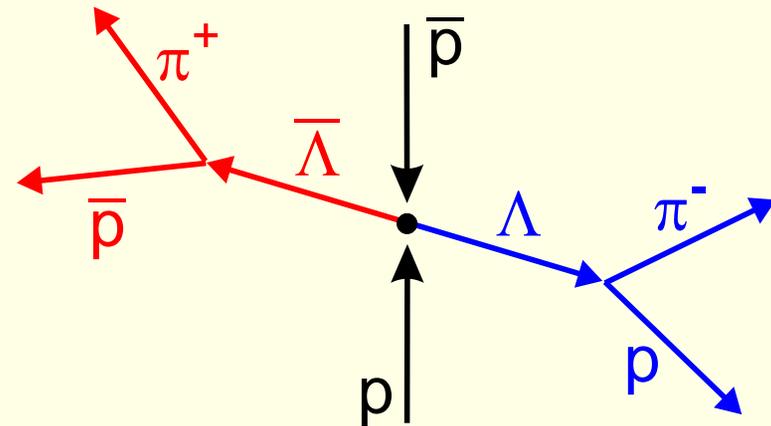
On the order of 1 billion events are needed for a 10^{-4} measurement

3. Control of systematics to the 10^{-4} level.



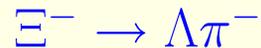
Producing polarized $\Lambda/\bar{\Lambda}$'s: $\bar{p}p \rightarrow \Lambda\bar{\Lambda}$

- Pioneered by PS185 at LEAR.
- Λ and $\bar{\Lambda}$ produced polarized: average polarization: 0.27.
- **Polarization of Λ and $\bar{\Lambda}$ rigorously equal by C-parity conservation.**
- Problem: $\sigma(\bar{p}p \rightarrow \Lambda\bar{\Lambda})$ small:
 - $65 \mu\text{b}$ @1.65 GeV/c
 - Total cross section: 100 mb.
- Gas jet target used to increase luminosity and to provide a point target.
- Much interest at CERN in early 90s in upgraded LEAR:
 - Target: $\rho = 10^{14}$ atoms/cm²
 - \mathcal{L} : 6.6×10^{31} cm⁻²s⁻¹
- Final event sample: 1.5×10^9
- These rates can be achieved at Fermilab now with an antiproton stacking rate that is four orders of magnitude more than was achieved at LEAR.
- Note: can also produce polarized $\Xi^-/\bar{\Xi}^+$ pairs.



Producing Polarized $\Lambda/\bar{\Lambda}$'s : unpolarized Ξ Decays

In this technique, pioneered by *HyperCP*, $\Lambda/\bar{\Lambda}$'s of known polarization are produced from **unpolarized** $\Xi^-/\bar{\Xi}^+$'s:



If the Ξ is produced unpolarized — which can simply be done by targeting at 0 degrees — then the Λ is found in a helicity state:

$$\vec{P}_\Lambda = \alpha_\Xi \hat{p}_\Lambda$$

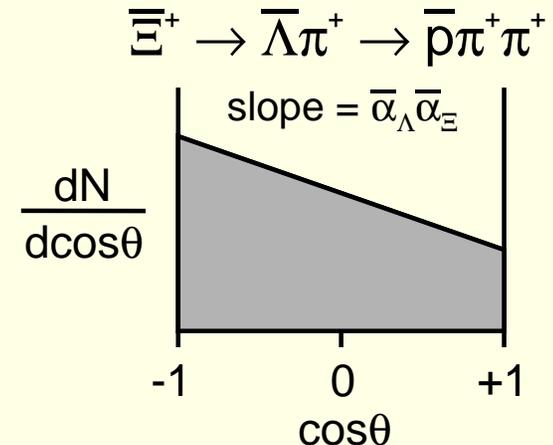
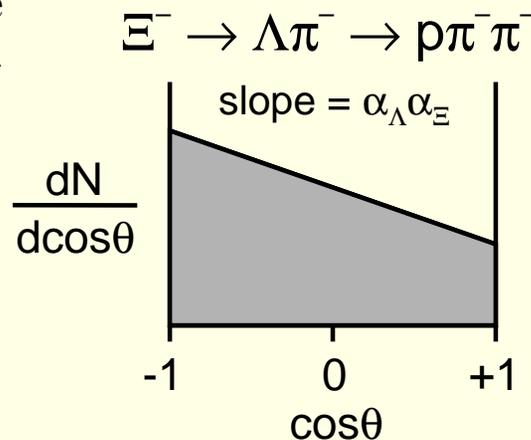
$$\vec{P}_{\bar{\Lambda}} = \bar{\alpha}_\Xi \hat{p}_{\bar{\Lambda}}$$

$$\frac{dN(p)}{d\cos\theta} = \frac{N_0}{2}(1 + \alpha_\Lambda\alpha_\Xi \cos\theta)$$

$$\frac{dN(\bar{p})}{d\cos\theta} = \frac{N_0}{2}(1 + \bar{\alpha}_\Lambda\bar{\alpha}_\Xi \cos\theta)$$

If *CP* is good, the slopes of the proton and antiproton $\cos\theta$ distributions are identical, and:

$$\alpha_\Xi\alpha_\Lambda = \bar{\alpha}_\Xi\bar{\alpha}_\Lambda$$



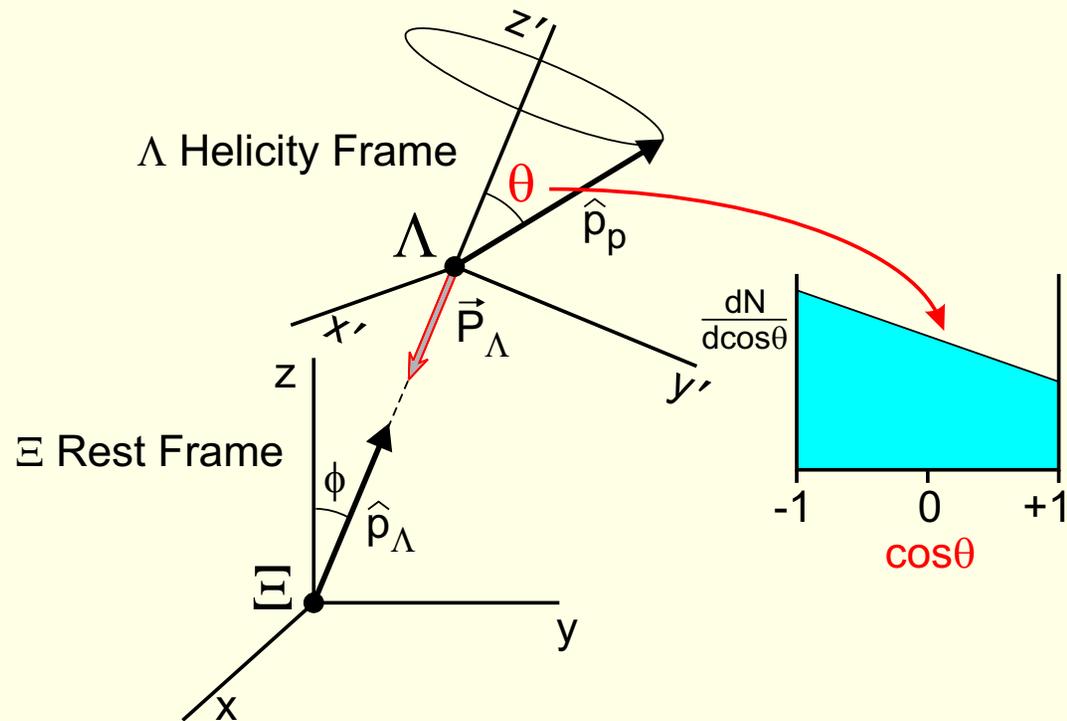
HyperCP technique is sensitive to both Ξ and Λ CP violation

$$\frac{\alpha_{\Xi}\alpha_{\Lambda} - \bar{\alpha}_{\Xi}\bar{\alpha}_{\Lambda}}{\alpha_{\Xi}\alpha_{\Lambda} + \bar{\alpha}_{\Xi}\bar{\alpha}_{\Lambda}} \approx A_{\Xi} + A_{\Lambda}$$

where: $A_{\Xi} = \frac{\alpha_{\Xi} + \bar{\alpha}_{\Xi}}{\alpha_{\Xi} - \bar{\alpha}_{\Xi}}$ and $A_{\Lambda} = \frac{\alpha_{\Lambda} + \bar{\alpha}_{\Lambda}}{\alpha_{\Lambda} - \bar{\alpha}_{\Lambda}}$

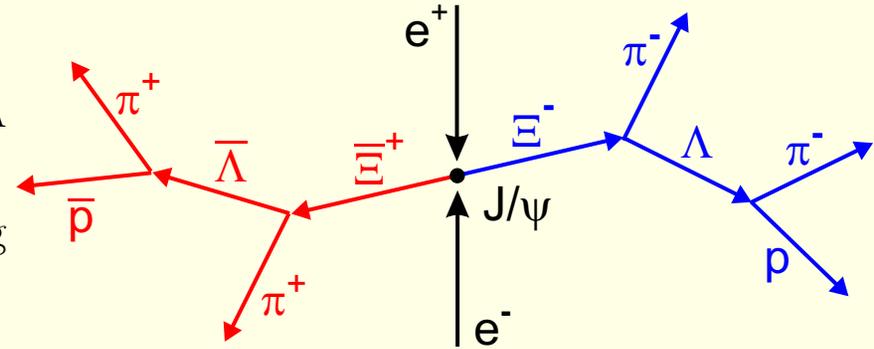
What HyperCP experimentally measures \Rightarrow

Important: polar axis changes from event to event.



$$e^+e^- \rightarrow J/\psi \rightarrow \Xi^-\bar{\Xi}^+$$

- Interest from τ -charm factory proponents.
- In $J/\psi \rightarrow \Lambda\bar{\Lambda}$ polarized beams needed as Λ and $\bar{\Lambda}$ not produced polarized.
- Unpolarized $\Xi^-\bar{\Xi}^+$ can be analyzed using the *HyperCP* technique to extract $A_{\Xi\Lambda}$.



- Small BR \Rightarrow lots of J/ψ 's needed to get to $\Delta A_{\Xi\Lambda} \approx 10^{-4}$:

	Mode	BR	$e^+e^- \rightarrow J/\psi$
1.0×10^9 events	$\Lambda\bar{\Lambda}$	$(1.3 \pm 0.12) \times 10^{-3}$	770×10^9
	$\Xi^-\bar{\Xi}^+$	$(1.8 \pm 0.4) \times 10^{-3}$	560×10^9

- Required luminosity large (100% acc, 1 yr running):

	σ_E [MeV]	$\sigma(e^+e^- \rightarrow J/\psi)$ [μb]	\mathcal{L} [$\text{cm}^{-2}\text{s}^{-1}$]
$1,000 \times 10^9 J/\psi$ events	1.0	2.8	36×10^{33}
	0.1	18.9	5.3×10^{33}
	0.0	51.6	1.9×10^{33}

- Higher luminosities, smaller σ_E still needed to get to goal of one billion events

	σ_E [MeV]	\mathcal{L} [$\text{cm}^{-2}\text{s}^{-1}$]
BEPC-II:	1.61	1×10^{33}
CESR-C:	2.48	0.035×10^{33}

What is the experimental situation?

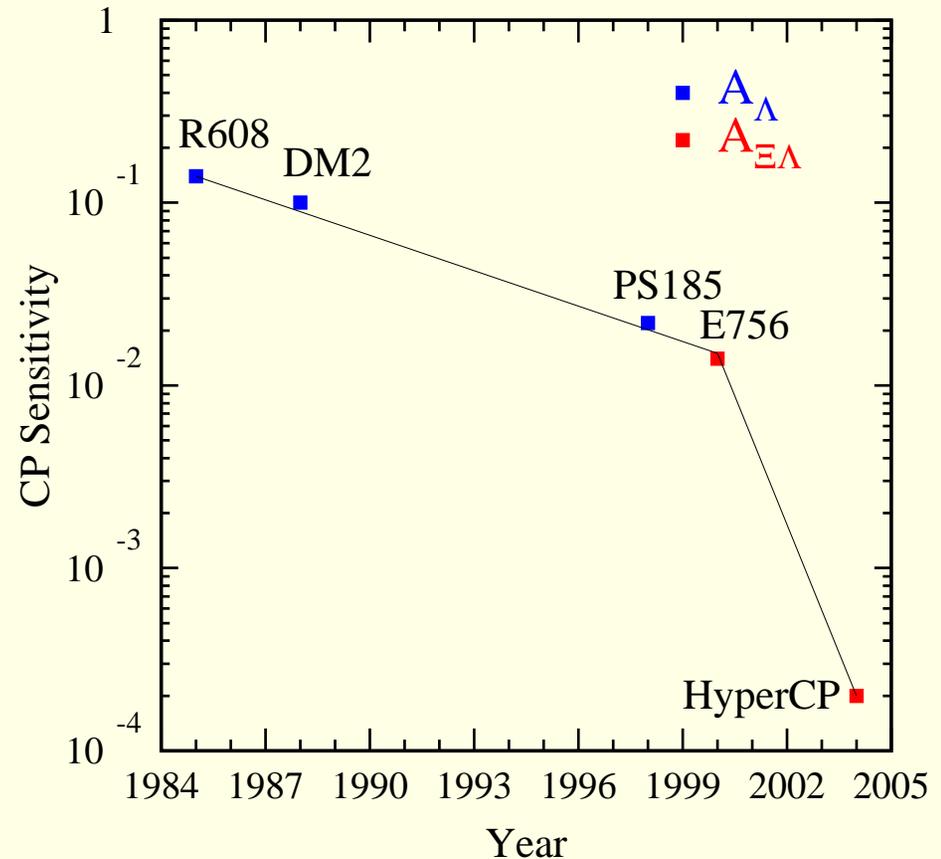
- To date there are only upper limits on the asymmetries.
- A_Λ has been measured to 2×10^{-2} :

Exp	Mode	Method
R608	A_Λ	$p\bar{p} \rightarrow \Lambda X, p\bar{p} \rightarrow \bar{\Lambda} X$
DM2	A_Λ	$e^+e^- \rightarrow J/\psi \rightarrow \Lambda\bar{\Lambda}$
PS185	A_Λ	$p\bar{p} \rightarrow \Lambda\bar{\Lambda}$

- There is a recent measurement of $A_{\Xi\Lambda}$, based on the *HyperCP* technique:

Exp	Mode	Method
E756	$A_{\Xi\Lambda}$	$pN \rightarrow \Xi^\pm X \rightarrow \Lambda\pi^\pm$

- This measurement of $A_{\Xi\Lambda}$ can be used with measurements of A_Λ to infer a limit on A_Ξ .
- None of these measurements is in the regime of testing theory.
- HyperCP* is pushing two orders of magnitude beyond the best limit, to $\sim 10^{-4}$.**



Phenomenology of CP Violation in Ξ and Λ Decay

- CP violation in Ξ and Λ decays is manifestly **direct** with $\Delta S = 1$.
- Three ingredients are needed to get a non-zero asymmetry:
 1. At least two channels in the final state: the S - and P -wave amplitudes.
 2. The CP violating weak phases must be different in the two channels.
 3. There must be unequal final-state scattering phase shifts in the two channels.

$$\begin{aligned}
 A_\Lambda &= (\alpha_\Lambda + \alpha_{\bar{\Lambda}})/(\alpha_\Lambda - \alpha_{\bar{\Lambda}}) \cong -\tan(\delta_P - \delta_S) \sin(\phi_P - \phi_S), \\
 A_\Xi &= (\alpha_\Xi + \alpha_{\bar{\Xi}})/(\alpha_\Xi - \alpha_{\bar{\Xi}}) \cong -\tan(\underbrace{\delta_P - \delta_S}_{\text{strong phases}}) \sin(\underbrace{\phi_P - \phi_S}_{\text{weak phases}}).
 \end{aligned}$$

- Asymmetry greatly reduced by the small strong phase shifts.
 - The $p\pi$ phase shifts have been measured to a precision of about one degree:

$$\Lambda \begin{cases} \delta_P = -1.1 \pm 1.0^\circ \\ \delta_S = 6.0 \pm 1.0^\circ \end{cases}$$

- The $\Lambda\pi$ phase shifts can't be directly measured, theoretical predictions disagree:

$$\Xi^- \left\{ \begin{array}{l} \delta_P = -2.7^\circ \\ \delta_S = -18.7^\circ \end{array} \right\}_{1965} \quad = \quad \left. \begin{array}{l} -1^\circ \\ 0^\circ \end{array} \right\}_{\text{recent } \chi PT}$$

HyperCP has measured the $\Lambda\pi$ phase shift: $(4.6 \pm 2.3)^\circ$

Measurement of the Λ - π Phase Shift

- This is done by analyzing the Λ decay distribution from 144 million **polarized** Ξ^- 's.
- Λ has three components of polarization:

$$\vec{P}_\Lambda = \frac{(\alpha_\Xi + \vec{P}_\Xi \cdot \hat{p}_\Lambda) \hat{p}_\Lambda + \beta_\Xi (\vec{P}_\Xi \times \hat{p}_\Lambda) + \gamma_\Xi (\hat{p}_\Lambda \times (\vec{P}_\Xi \times \hat{p}_\Lambda))}{(1 + \alpha_\Xi \vec{P}_\Xi \cdot \hat{p}_\Lambda)}$$

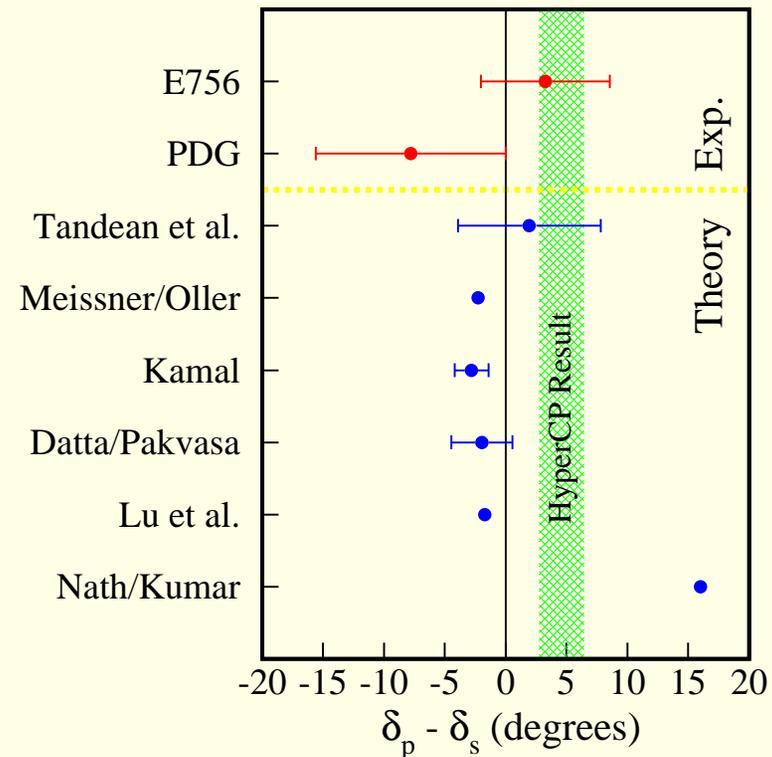
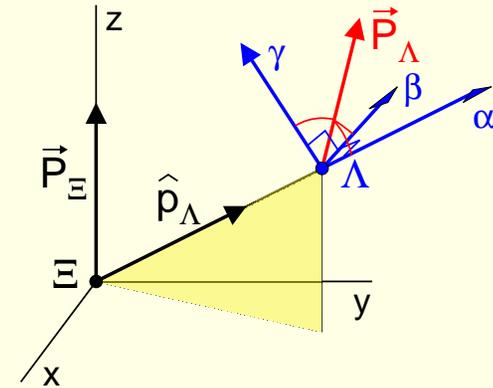
$$\beta_\Xi = -0.037 \pm 0.011(\text{stat}) \pm 0.010(\text{syst})$$

$$\gamma_\Xi = 0.888 \pm 0.0004(\text{stat}) \pm 0.006(\text{syst})$$

- Using the known value of α_Ξ :

$$\delta_P - \delta_S = \tan^{-1} \left(\frac{\beta_\Xi}{\alpha_\Xi} \right) = (4.6 \pm 1.4 \pm 1.2)^\circ$$

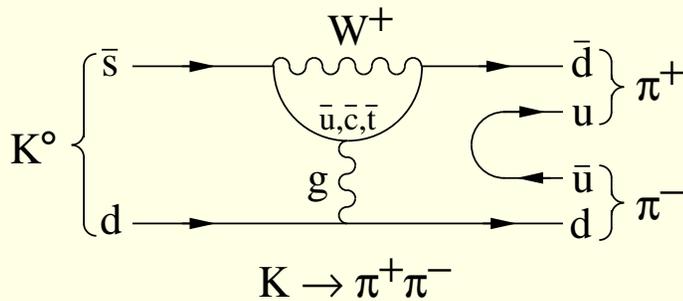
- First non-zero measurement of phaseshift.
- This is about the same magnitude as the p - π phase shift:
 - \Rightarrow CP equally likely in Ξ and Λ decays.
 - \Rightarrow CP predictions underestimated,
 - \Rightarrow χ PT calculations off.



Comparison of ϵ'/ϵ and A_{Ξ}, A_{Λ}

ϵ'/ϵ

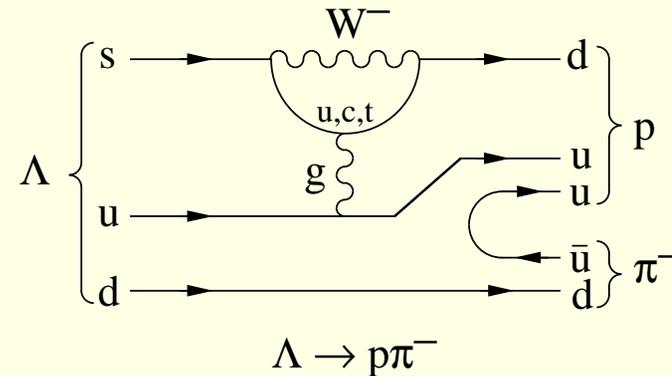
- Thought to be due to the Penguin diagram in the Standard Model.



- Expressed through a different CP -violating phase in the $I = 0$ and $I = 2$ amplitudes.
- Probes only parity violating amplitudes.

$A_{\Xi\Lambda}$

- Thought to be due to the Penguin diagram in the Standard Model.



- Expressed through a different CP -violating phase in the S - and P -wave amplitudes.
- Probes parity violating and conserving amplitudes.

“Our results suggest that this measurement is complementary to the measurement of ϵ'/ϵ , in that it probes potential sources of CP violation at a level that has not been probed by the kaon experiments.”

CP Violation and Theory

What have theorists contributed in the course of 25 years toward a quantitative understanding of CP violation?

Nothing.

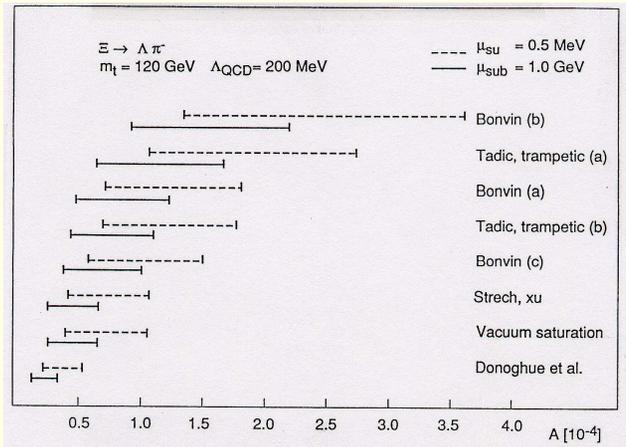
A. Pais

“CP Violation in Particle Physics and Astrophysics”

1989

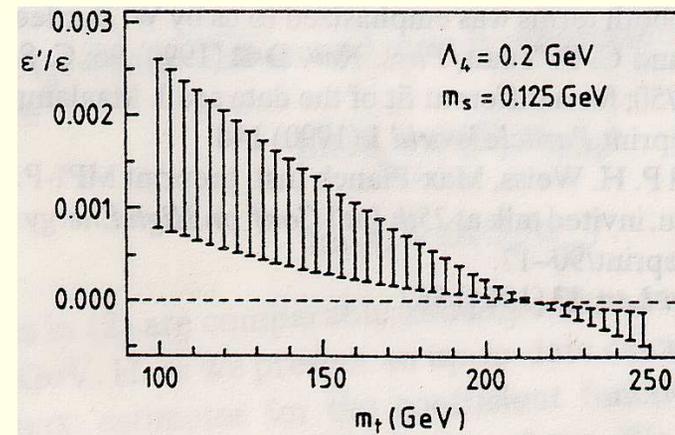
Bad News: Standard Model Theory Predictions Small

- Much enthusiasm a decade ago as Standard Model predictions were relatively large.



Valencia (1991)

- At same time there was concern that accidental cancellation in the kaon system would lead to $\epsilon'/\epsilon \approx 0$.



Paschos (1991)

- Standard Model predictions have slowly fallen to:

$$-0.5 \times 10^{-4} < A_{\Xi\Lambda} < +0.5 \times 10^{-4}$$

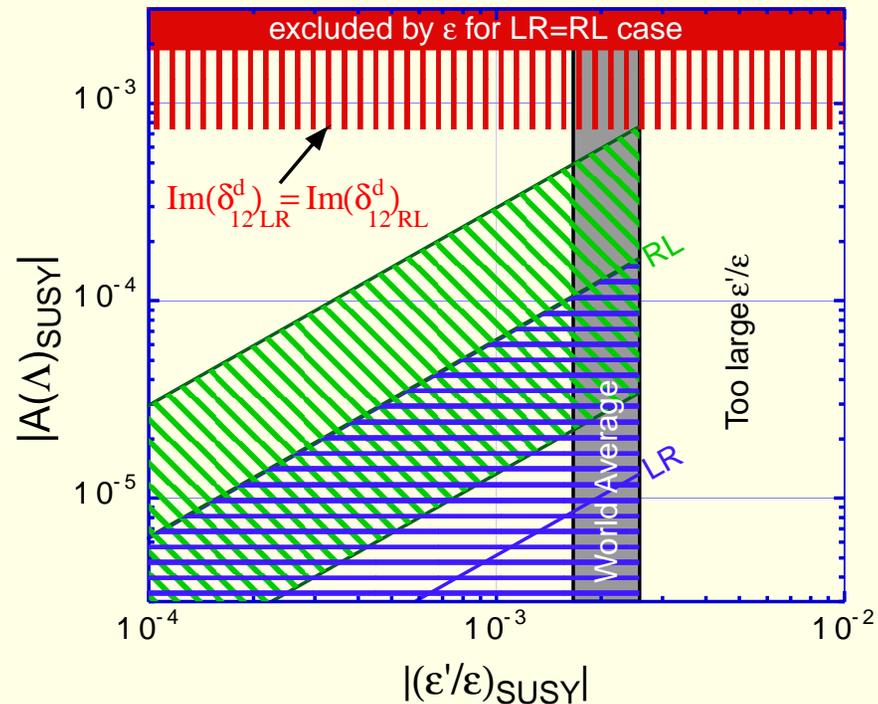
(Tandean & Valencia, 2003)

- The expected SM asymmetry is out of reach for any experiment, planned or otherwise.

Important: no unambiguous connection between: $\delta_{\text{CKM}} \Leftrightarrow A_{\Xi}, A_{\Lambda}$

Good News: Standard Model Theory Predictions Small

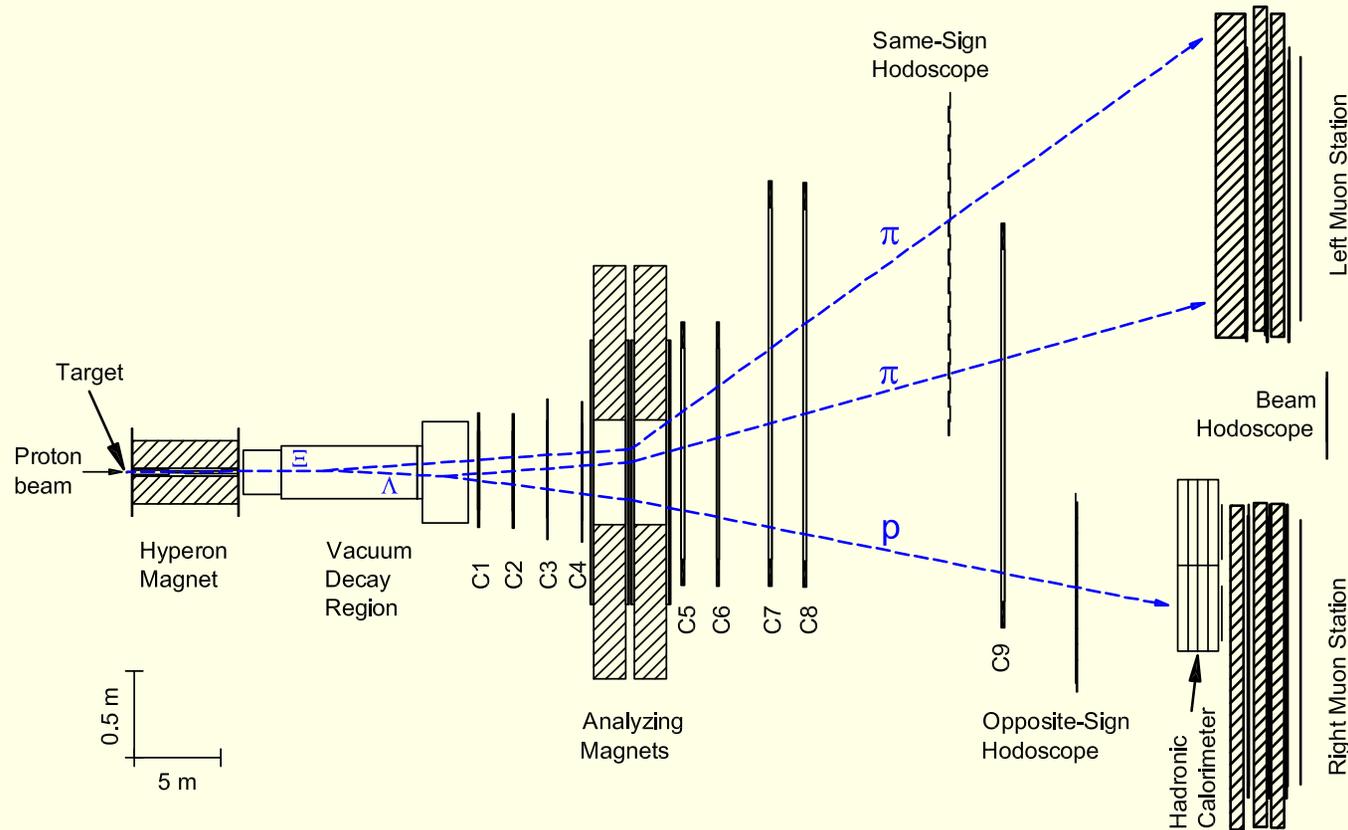
- Beyond-the-standard-model predictions larger, and not well constrained by kaon CP measurements: hyperon CP violation probes both parity conserving and parity violating amplitudes.
- Recent paper by Tandean (2004) shows that the upper bound on $A_{\Xi\Lambda}$ from ϵ'/ϵ and ϵ measurements is $\sim 100 \times 10^{-4}$.
- For example, some supersymmetric models that do not generate ϵ'/ϵ can lead to A_{Λ} of $O(10^{-3})$.
- Other BSM theories, such as Left-Right mixing models, (Chang, He, Pakvasa (1994)), also have enhanced asymmetries.



He et al., PRD 61 (2000) 071701(R).

Any CP -violation signal will almost certainly come from New Physics.

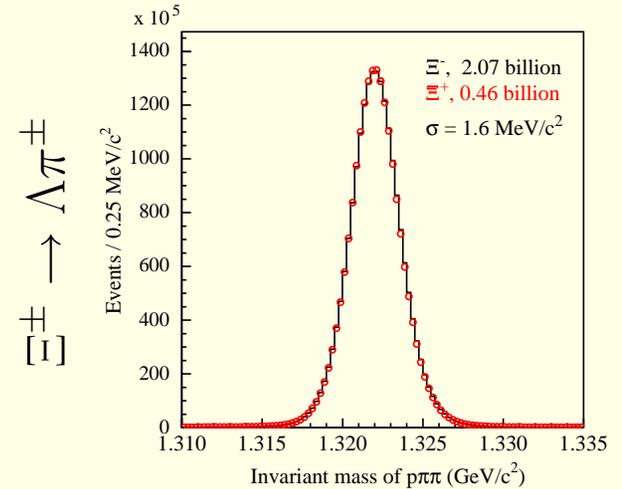
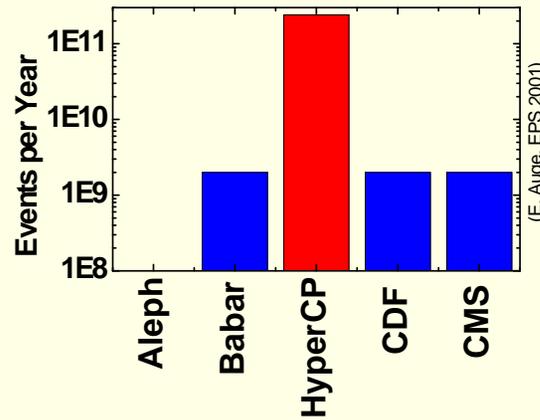
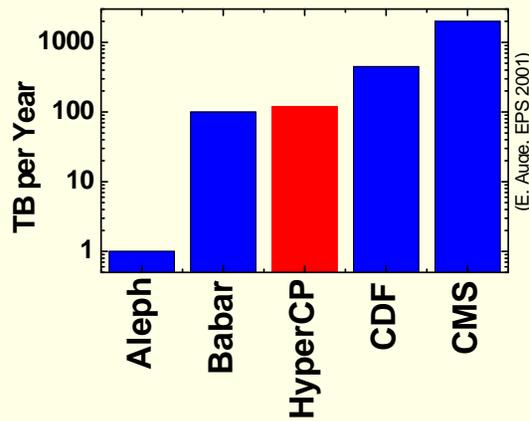
The HyperCP Spectrometer



- Alternate + and - running.
- 800 GeV/c incident proton beam.
- 10–15 MHz, 167 GeV/c charged beam.
- High-rate, narrow-pitch wire chambers.
- Muon system for rare/forbidden hyperon and kaon decays.
- Very high-rate DAQ:
 - 50-80 KHz evts/spill-s to tape.
 - 27 MB/s on 27 Exabyte 8705 tape drives.
- Simple, low-bias trigger using hodoscopes and calorimeter.
 - SS(≥ 1 hit) · OS(≥ 1 hit) · Cal(≥ 40 G eV)

HyperCP Yields

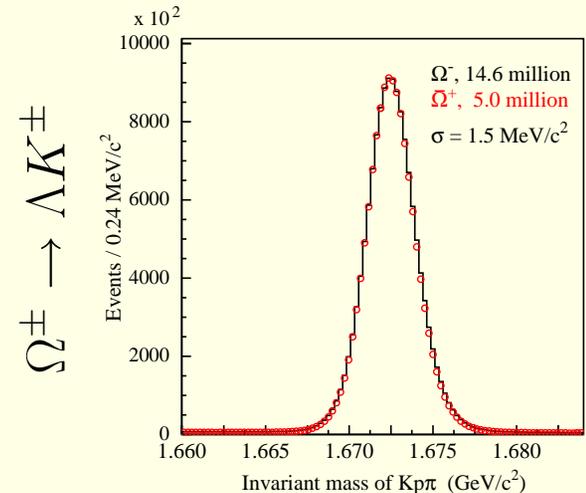
- In 12 months of data taking *HyperCP* recorded one the largest data samples ever by a particle physics experiment: 231 billion events, 29,401 tapes, and 119.5 TB data.



Entire WWW on 9/11/01 was **5 TB!**

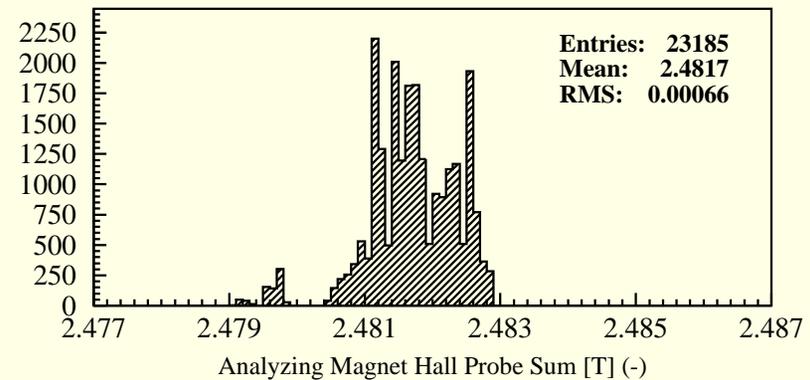
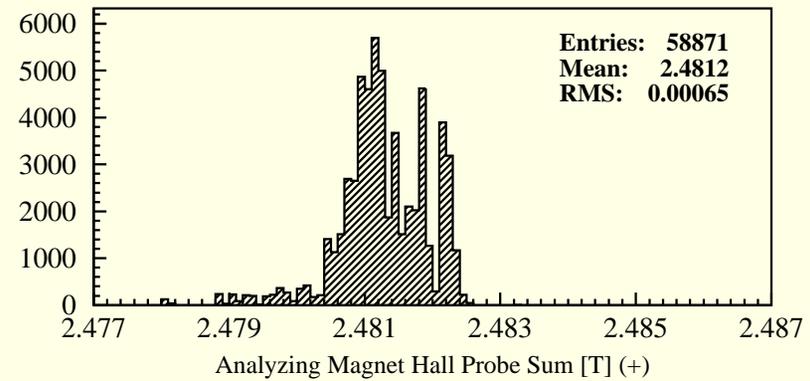
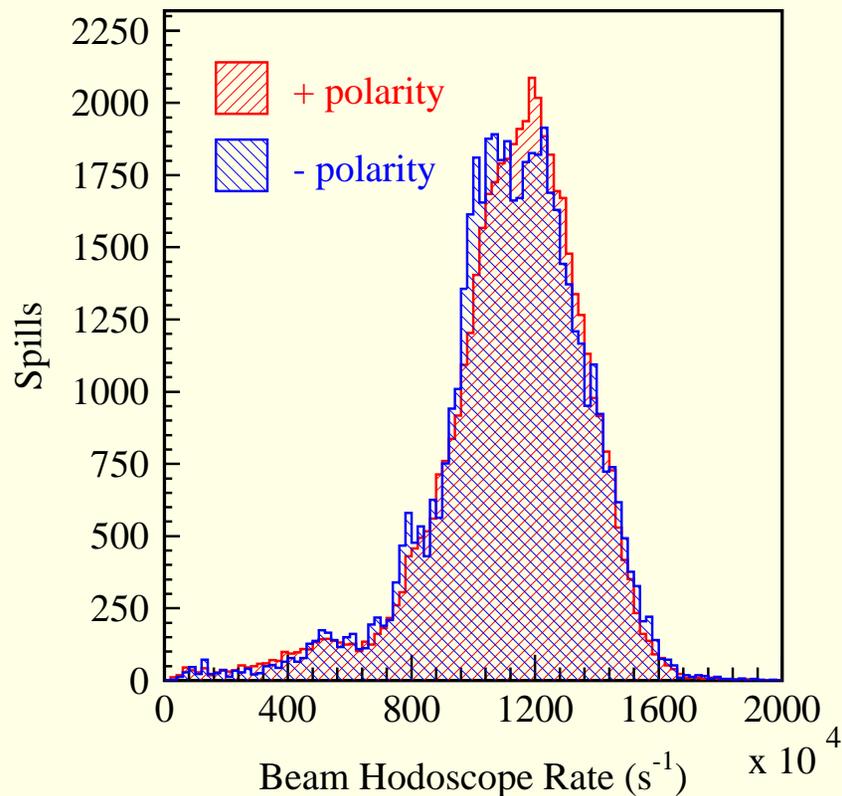
Reconstructed Events

Type	Channeled beam polarity		Total
	+	-	
$\Xi \rightarrow \Lambda\pi$	458×10^6	2032×10^6	2490×10^6
$K \rightarrow \pi\pi\pi$	391×10^6	164×10^6	555×10^6
$\Omega \rightarrow \Lambda K$	4.9×10^6	14.1×10^6	19.0×10^6



Care Taken to Mimimize Differences in + and - Running

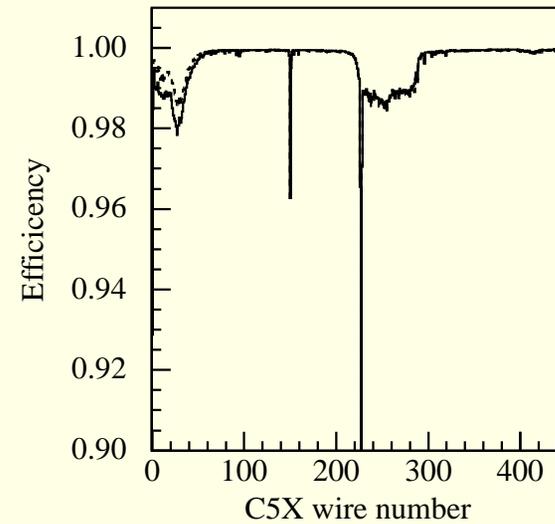
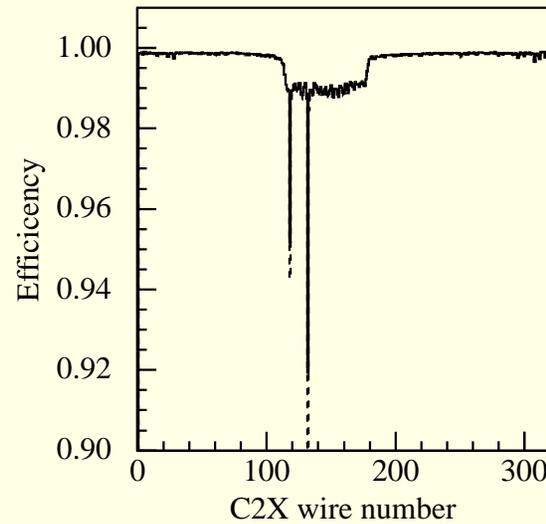
- Target length changed to equalize channeled beam rates.
 - + polarity: 2.0 cm Cu
 - polarity: 6.0 cm Cu
- When flipping polarity, field magnitude kept within $\sim 2 \times 10^{-4}$.
- This corresponds to a ~ 0.3 mm deflection difference at 10 m for the lowest momentum (~ 10 GeV/c pions).



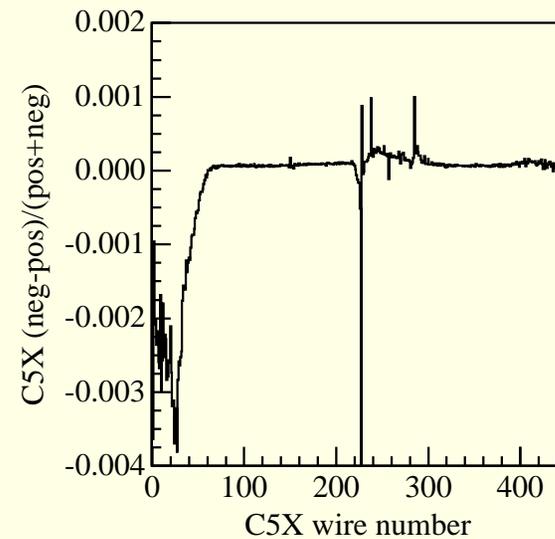
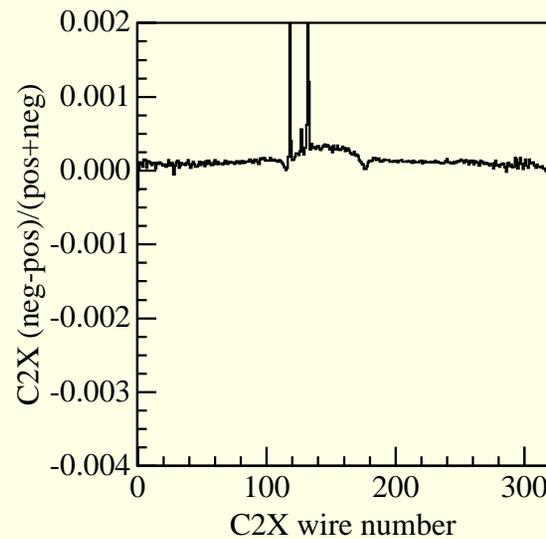
Little Difference in PWC Efficiencies from + and - Running

- - data: solid line
- + data: dashed line
- 32 total planes \Rightarrow good redundancy

Absolute efficiency



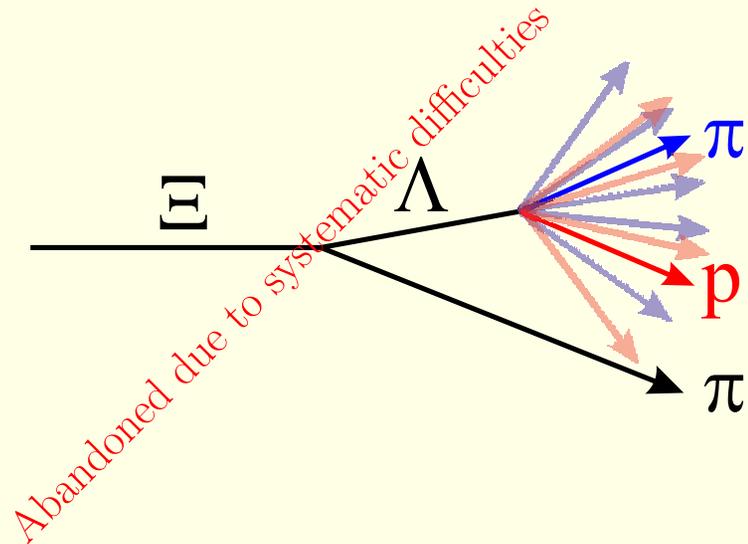
Difference (Neg. - Pos.)



Two Different CP Analyses Being Done

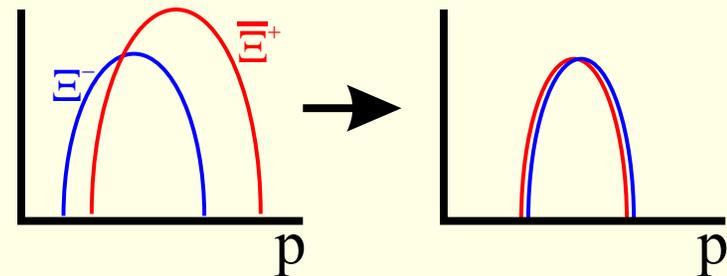
Hybrid Monte Carlo Method:

- Compare corrected $\cos \theta$ distributions.
- Take a real $\Xi \rightarrow \Lambda \pi$, $\Lambda \rightarrow p \pi$ event, discard proton and pion, generate 10 new unpolarized Λ decays.
- **Advantage:** Absolute measurement of $\alpha_{\Lambda} \alpha_{\Xi}$.
- **Disadvantage:** Monte Carlo must be very, very good, and fast: ~ 20 billion events needed.



Weighting Method:

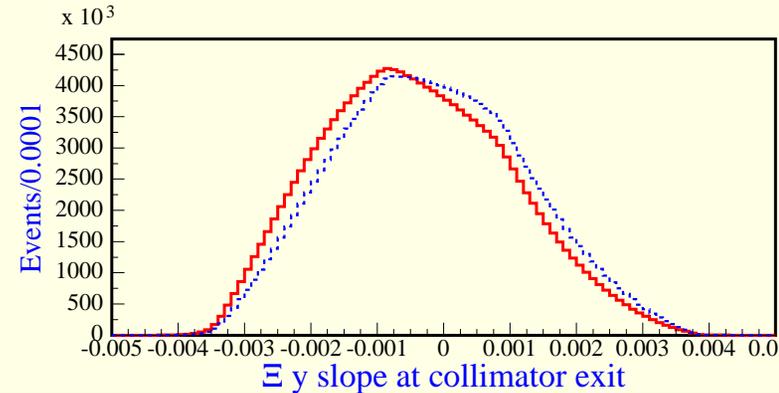
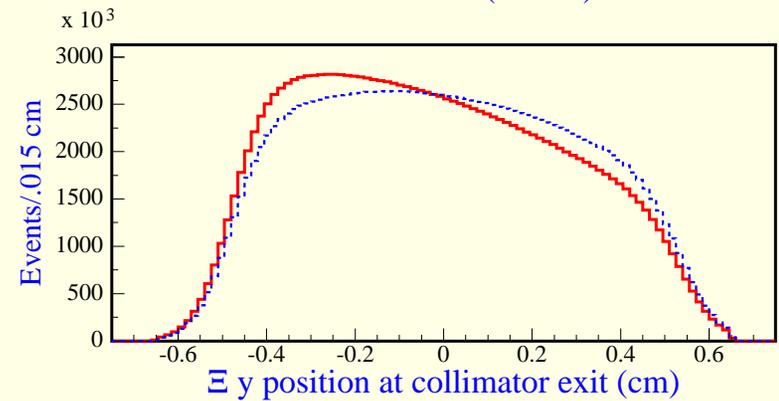
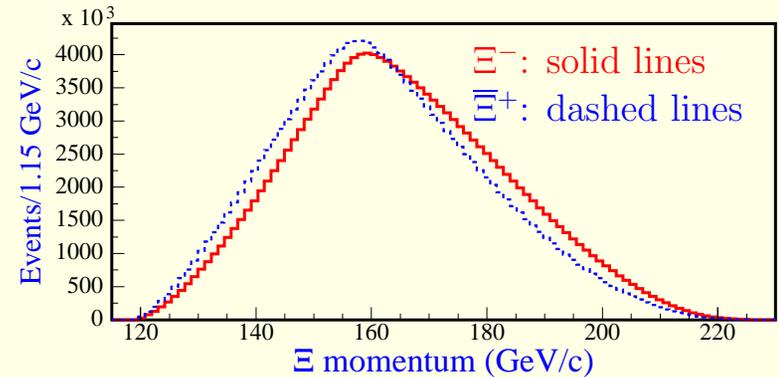
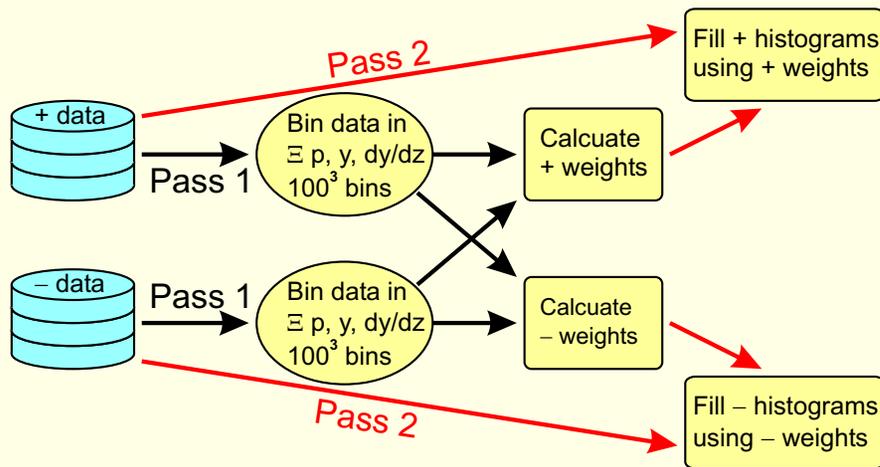
- Compare uncorrected $\cos \theta$ distributions.
- Force the Ξ^- and Ξ^+ events to have similar momentum and spatial distributions by appropriate weighting.
- **Advantage:** No Monte Carlo needed to measure apparatus acceptance, smaller statistical error.
- **Disadvantage:** inflexible, event-size dependent analysis.



Large data set, ~ 1 billion events, in both cases makes the analysis difficult.

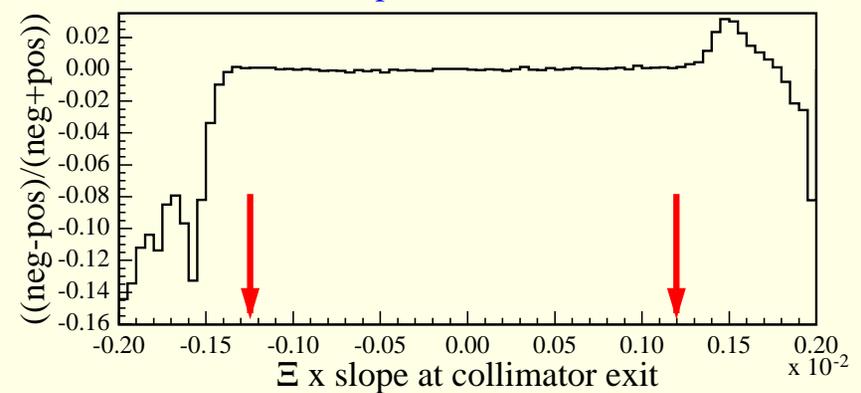
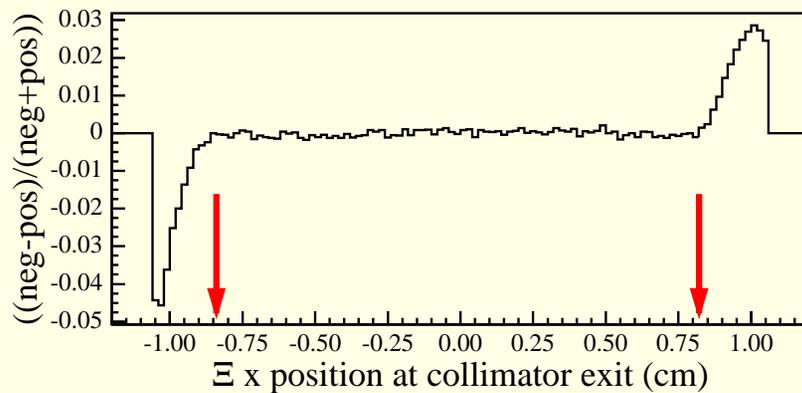
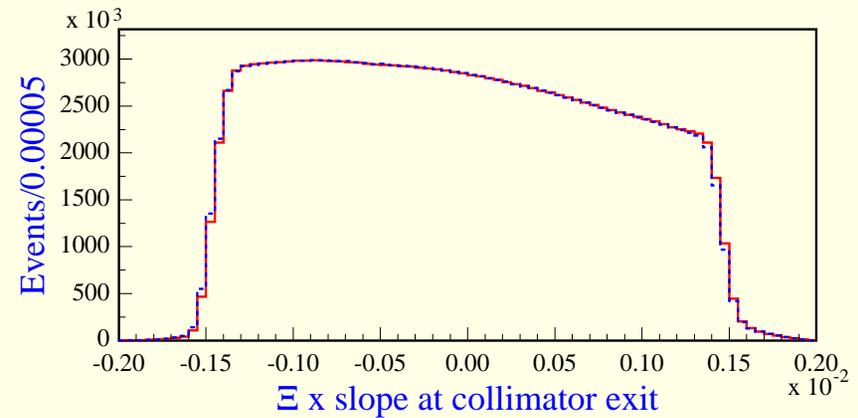
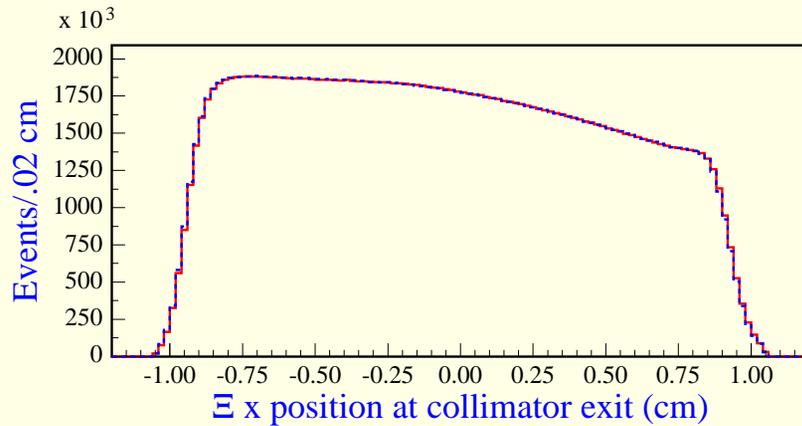
Weighting Technique

- **Problem:** Geometrical acceptance identical for Ξ^- and Ξ^+ decay products only if parent Ξ^- and Ξ^+ have same momentum and inhabit the same phase space exiting the collimator.
- That is not the case due to different production dynamics.
- **Solution:** Weight the Ξ^- and Ξ^+ events to force the two distributions to be identical.
- $100 \times 100 \times 100 = 1 \times 10^6$ bins used.



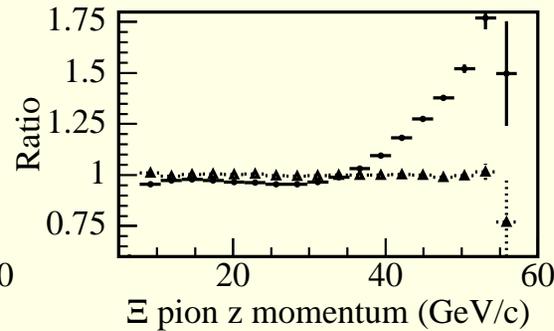
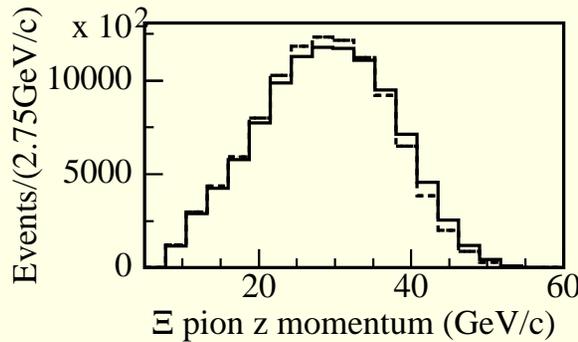
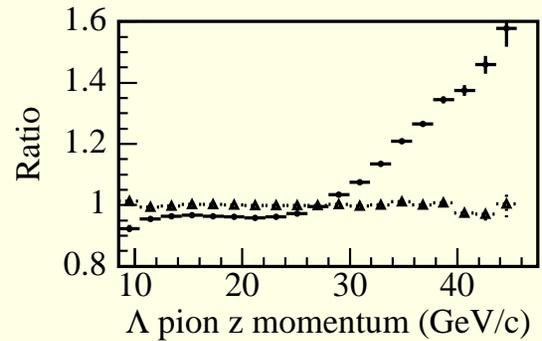
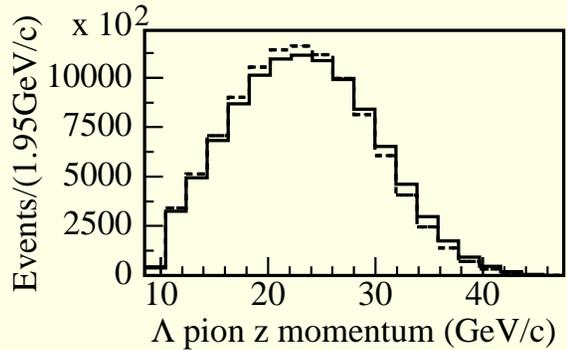
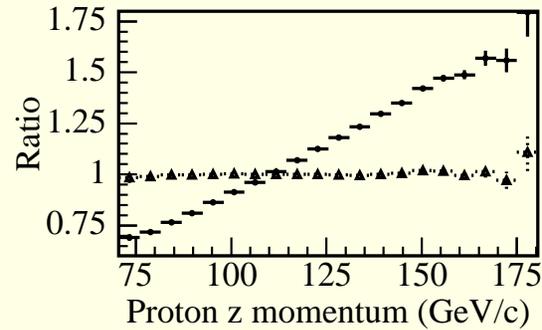
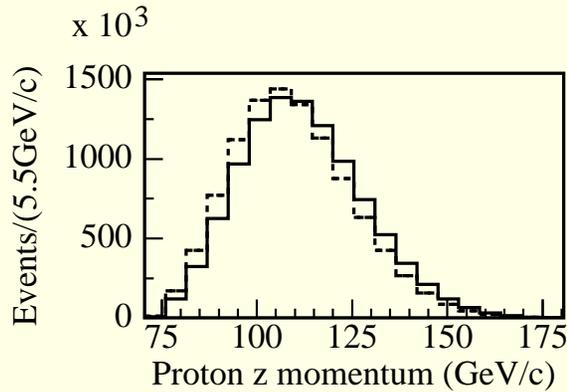
Ξ^- and Ξ^+ x Slopes and Positions not Weighted

- Not momentum dependent \Rightarrow distributions almost identical
- Cut out regions where they are not.
- Ξ^- : Solid lines
- Ξ^+ : Dashed lines



Proton, Λ -pion, Ξ -pion Momenta Before/After Weighting

— Solid lines
+ dashed lines



Ratio

o: before weighting
 Δ : after weighting

Extracting the CP Asymmetry

- Determine weighted proton and weighted antiproton $\cos \theta$ distributions.

$$\frac{dN_-}{d \cos \theta_-} = A_- \frac{N_-}{2} (1 + \alpha_{\Xi} \alpha_{\Lambda} \cos \theta_-)$$

$$\frac{dN_+}{d \cos \theta_+} = A_+ \frac{N_+}{2} (1 + \bar{\alpha}_{\Xi} \bar{\alpha}_{\Lambda} \cos \theta_+)$$

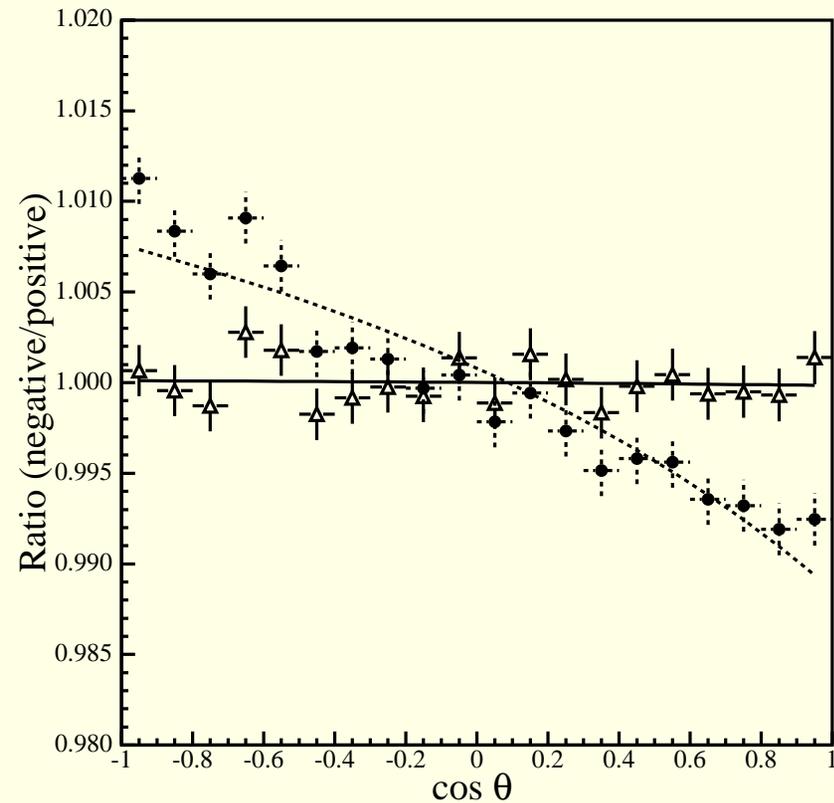
- Assume the acceptances A_- and A_+ have the same $\cos \theta$ dependence.
- Take the ratio of proton and antiproton $\cos \theta$ distributions and fit to:

$$R(\theta, \delta) = C \frac{1 + \alpha_{\Xi} \alpha_{\Lambda} \cos \theta}{1 + (\alpha_{\Xi} \alpha_{\Lambda} - \delta) \cos \theta}$$

to extract asymmetry δ :

$$\begin{aligned} \delta &= \alpha_{\Xi} \alpha_{\Lambda} - \bar{\alpha}_{\Xi} \bar{\alpha}_{\Lambda} \\ A_{\Xi\Lambda} &= \frac{\delta}{\alpha_{\Xi} \alpha_{\Lambda} + \bar{\alpha}_{\Xi} \bar{\alpha}_{\Lambda}} = \frac{\delta}{2\alpha_{\Xi} \alpha_{\Lambda}} \\ &= 1.71\delta \end{aligned}$$

- Note: acceptances cancel out!



Proton $\cos \theta$ ratio before (●) and after (Δ) weighting.

Monte Carlo Tests

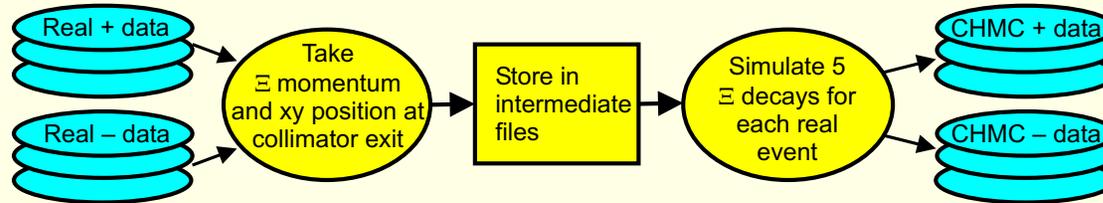
Important! Monte Carlo only used to:

- Verify code and algorithm.
- Study a few systematics.

Final result has no Monte Carlo dependence!

Problem: How do you generate ~ 1 billion MC events?

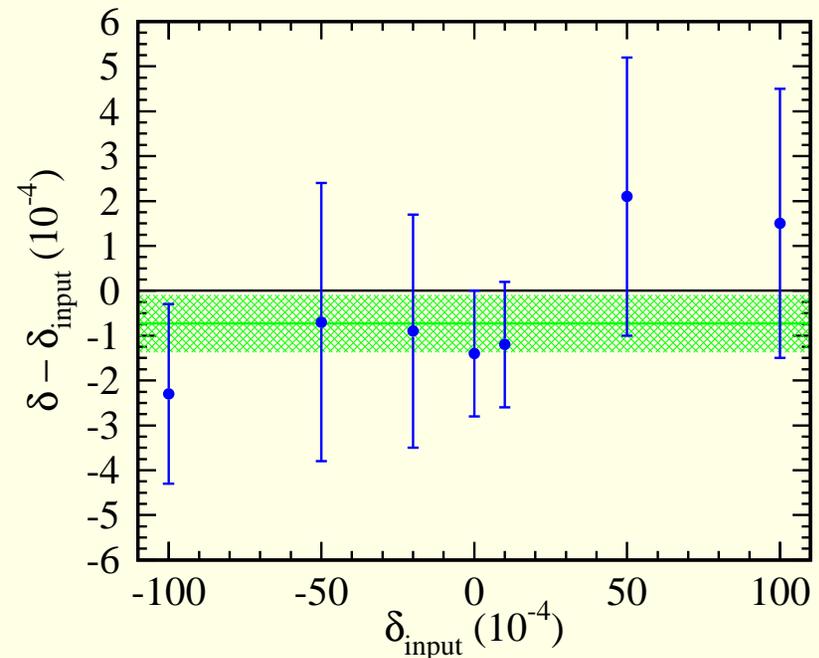
Solution:



We get the input asymmetry back \implies

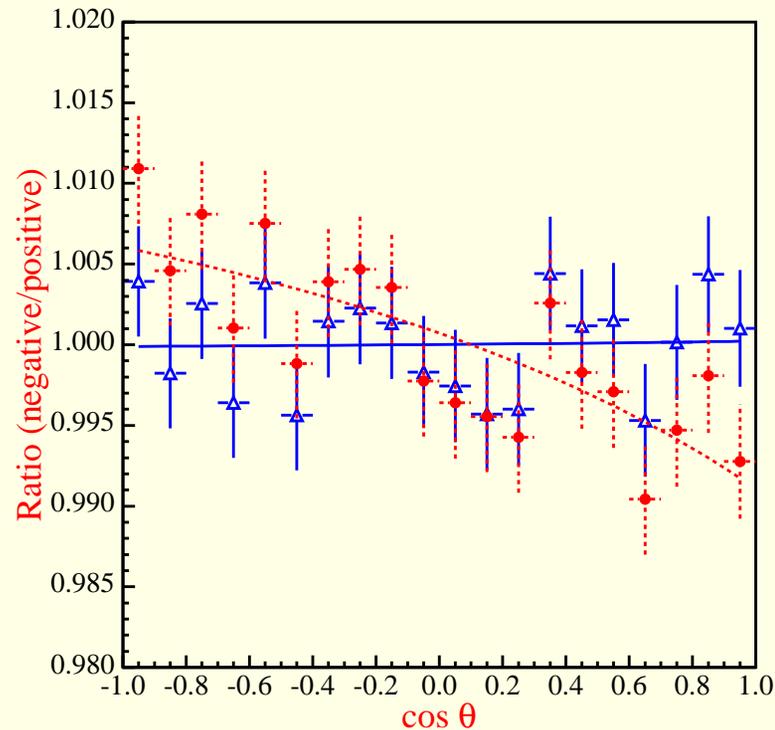
$$\delta = (-0.73 \pm 0.64) \times 10^{-4}$$

$$A_{\Xi\Lambda} = (1.24 \pm 1.09) \times 10^{-4}$$



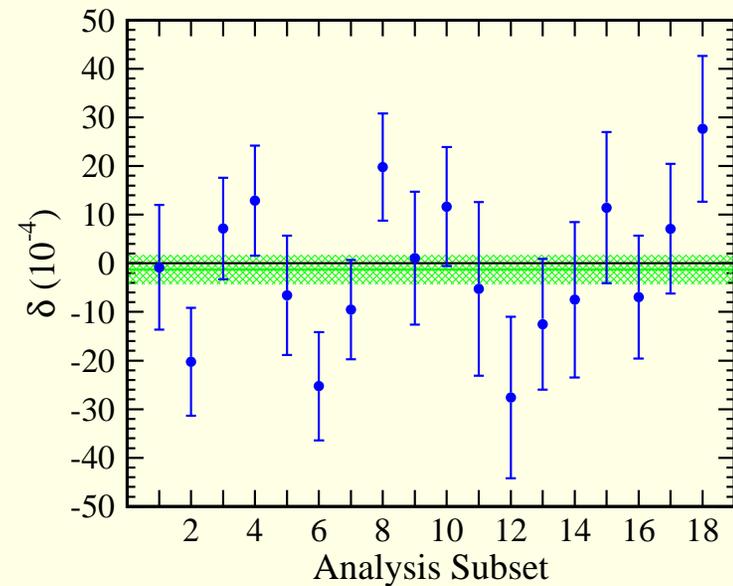
The CP Asymmetry $A_{\Xi\Lambda}$ from Weighting Method

- Data broken up into 18 sets, each with positive and negative events.
- No acceptance corrections.
- No efficiency corrections.
- No background subtraction.



Proton $\cos \theta$ ratio before (\bullet) after (Δ) weighting, from Analysis Set 1

$$\delta = \alpha_{\Xi}\alpha_{\Lambda} - \bar{\alpha}_{\Xi}\bar{\alpha}_{\Lambda}$$

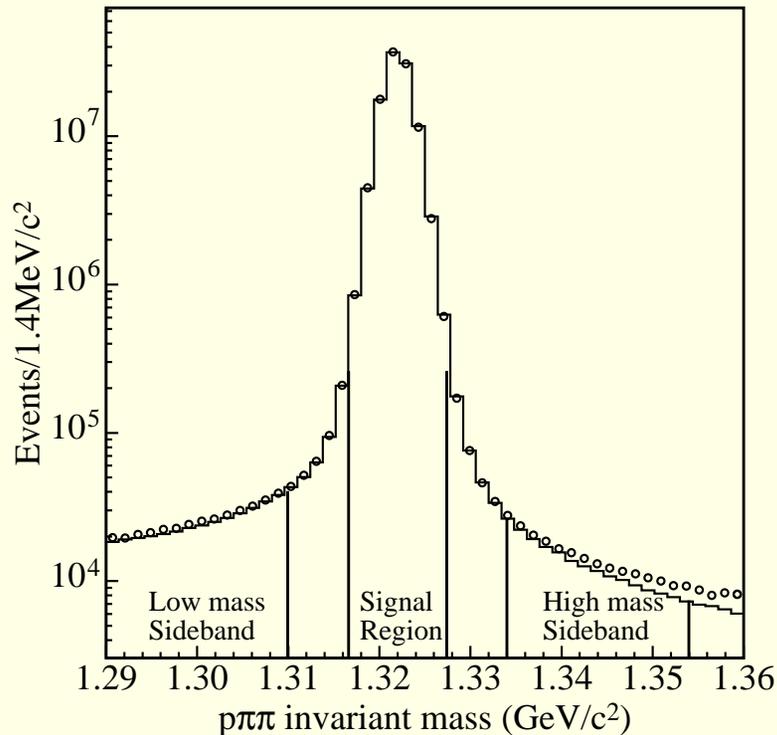


Weighted average of all 18 data sets:

$$\begin{aligned} \delta &= (-1.3 \pm 3.0) \times 10^{-4} \\ A_{\Xi\Lambda} &= (2.2 \pm 5.1) \times 10^{-4} \\ \chi^2 &= 24 \end{aligned}$$

Background Subtraction Has Little Effect

- Triple Gaussian fit with fourth-order polynomial for background.
- Background fraction:
 - Ξ^- : 0.43% (lines)
 - Ξ^+ : 0.41% (circles)

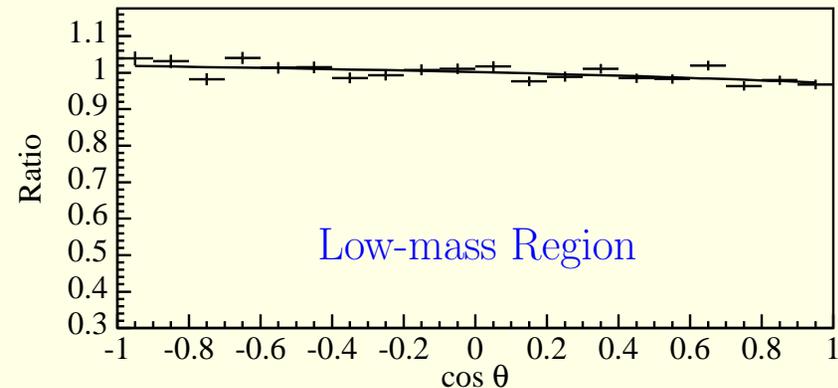
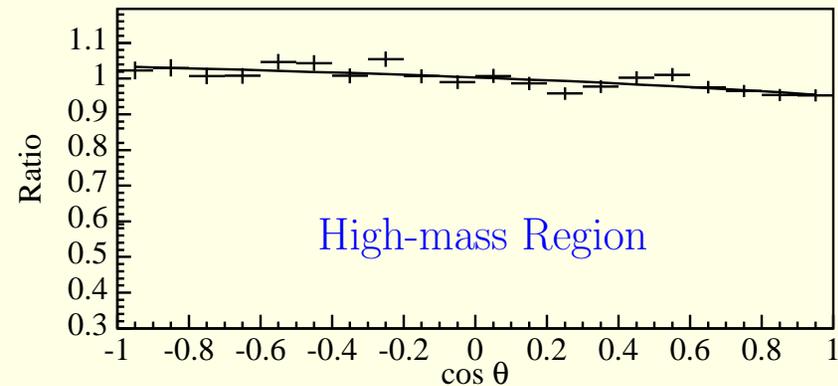


Low mass: $\delta = (-2.2 \pm 0.5) \times 10^{-2}$

High mass: $\delta = (-3.8 \pm 0.7) \times 10^{-2}$

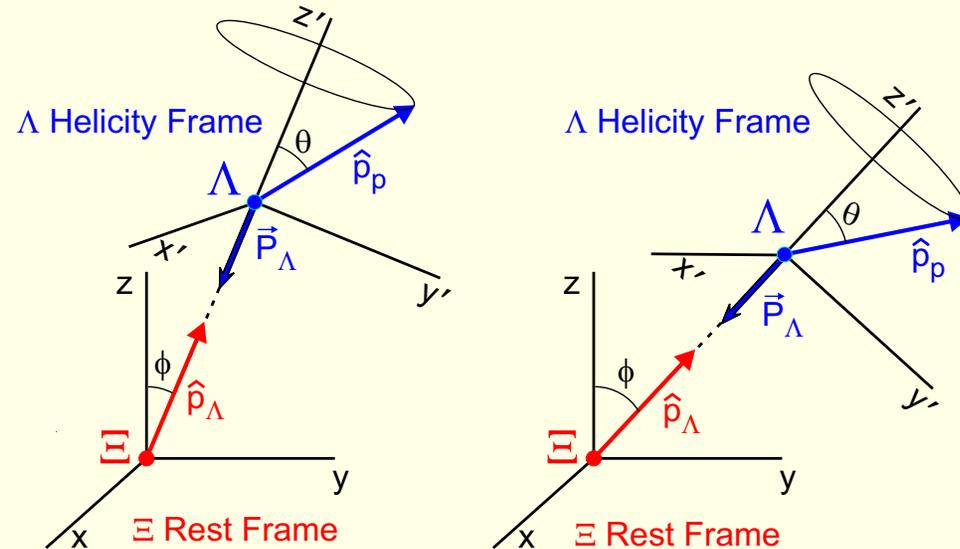
- Weighted background asymmetry:

$$A_{\Xi\Lambda}(bs) = (0.0 \pm 5.1) \times 10^{-4}$$

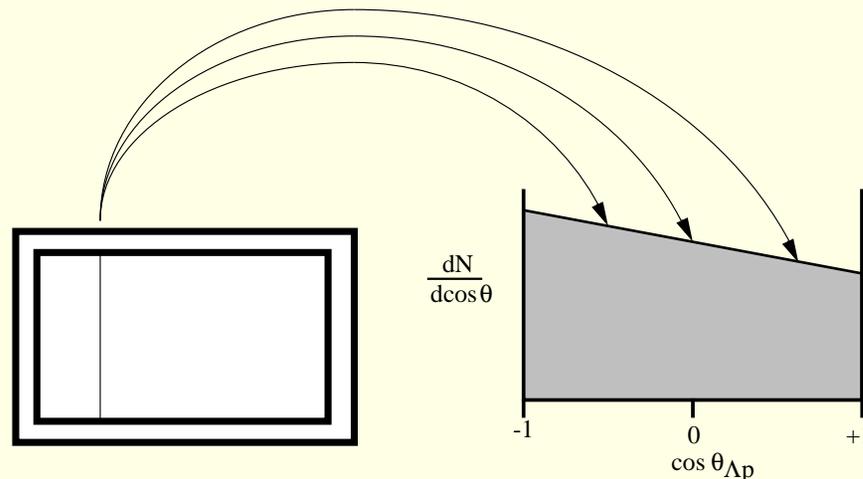


Helicity Frame Analysis Naturally Minimizes Biases

- The **helicity frame** axes change from event to event since we always define the polar axis to be the direction of the Λ momentum in the Ξ rest frame.



- Acceptance differences localized in a particular part of the apparatus do **not** map into a particular part of the proton (antiproton) $\cos \theta$ distribution.



Important! Overall acceptance differences do not cause any biases.

Weighted Analysis Bias Error Summary

Systematic	Method	$\delta A_{\Xi\Lambda}(10^{-4})$
Analyzing Magnets field uncertainties	Data	2.8
Calorimeter inefficiency uncertainty	Data	2.1
Validation of analysis code	CHMC	1.9
Collimator exit x slope cut	Data	1.4
Collimator exit x position cut	Data	1.2
PWC inefficiency uncertainty	CHMC	1.0
Hodoscope inefficiency uncertainty	Data	0.3
Particle/antiparticle interaction differences	MC	0.9
Momentum weights bin size	Data	0.4
Background subtraction uncertainty	Data	0.3
Error on α_{PDG}	Data	0.03
Polarization	MC	negligible
Earth's magnetic field	CHMC	negligible
Total systematic error		4.2

Results from CP Violation Search

Weighting Technique:

- $\sim 10\%$ total data sample
- selected from end of 1999 run
- 118.6 million Ξ^-
- 41.9 million Ξ^+
- no acceptance or efficiency corrections

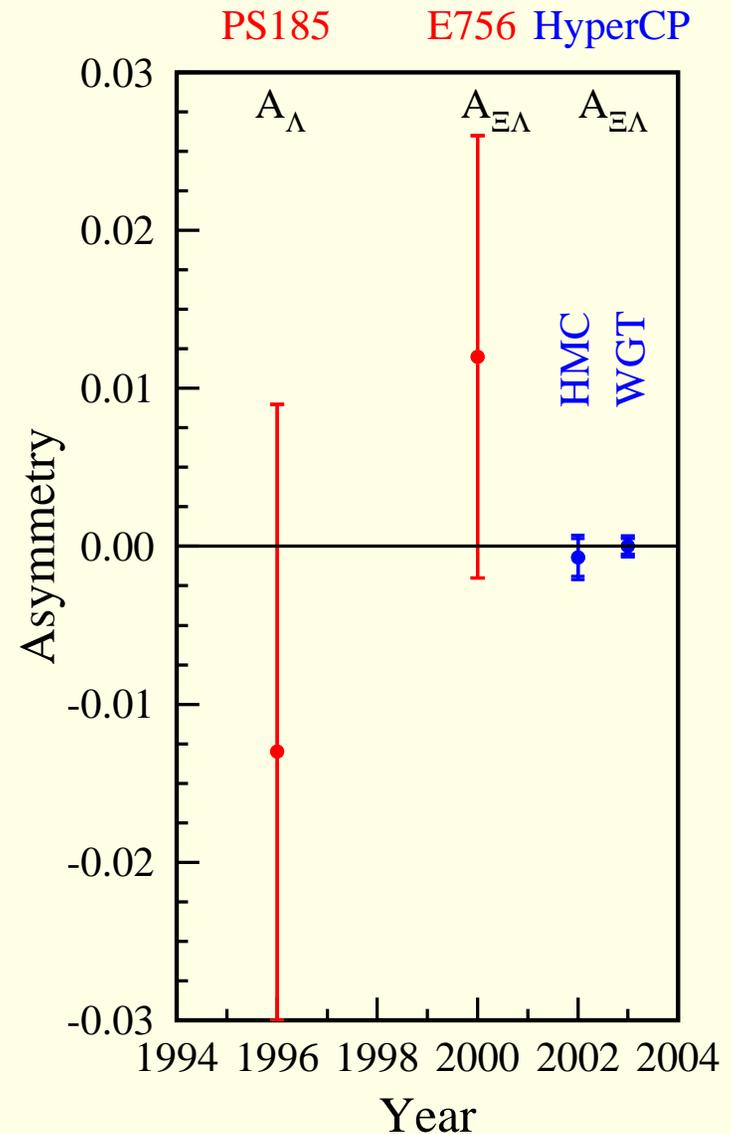
$$A_{\Xi\Lambda} = [0.0 \pm 5.1(\text{stat}) \pm 4.2(\text{syst})] \times 10^{-4}$$

Check with HMC Technique:

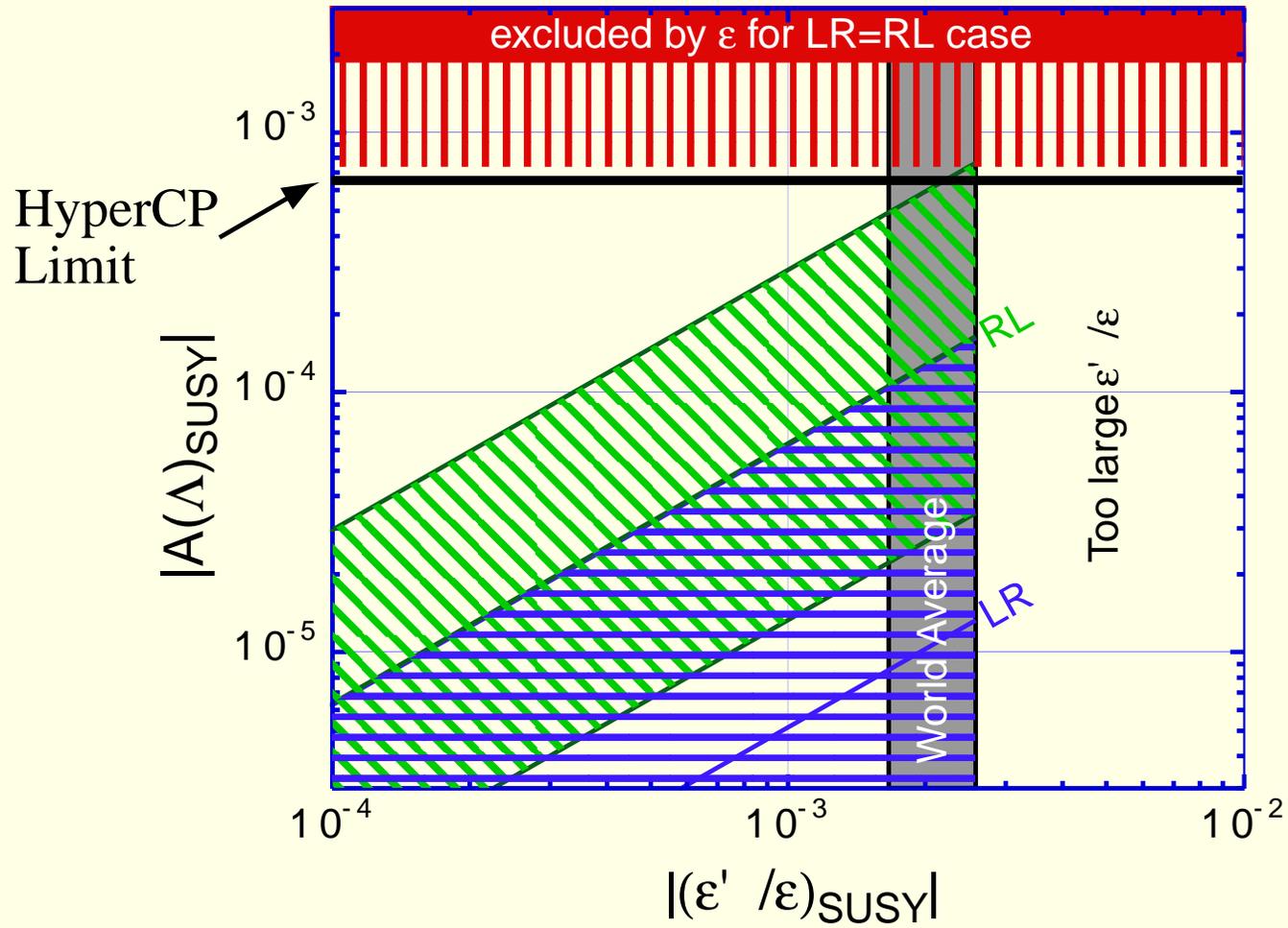
- $\sim 5\%$ of the total data sample
- prescaled selection of 1997 and 1999
- 15 million Ξ^-
- 30 million Ξ^+

$$A_{\Xi\Lambda} = [-7 \pm 12(\text{stat}) \pm 6.2(\text{syst})] \times 10^{-4}$$

$\Rightarrow 20\times$ improvement on previous result.



New HyperCP Result Constraining SUSY Models



Conclusions and Outlook

- Hyperon CP violation measurements — which are still in their infancy — are beginning to make an important impact on the CP violation landscape.
- These measurements are probing limits not constrained by Kaon, B, or EDM measurements.

“...we can then conclude that the available preliminary measurement by HyperCP has already begun to probe the parity-even contributions better than ϵ does.”

Tandean (2004)

- $HyperCP$, in particular, the first dedicated hyperon CP violation experiment, has pushed into the region where SUSY models allow an effect.
- Shortly $HyperCP$ should push the statistical limit to
$$\delta A_{\Xi\Lambda} \approx 2 \times 10^{-4}$$
- No reason why the $HyperCP$ technique cannot be pushed at least another order of magnitude farther in statistics: $\delta A_{\Xi\Lambda} \approx 0.5 \times 10^{-4}$, which would be a very interesting result.
- Beyond $A_{\Xi\Lambda} \approx 0.5 \times 10^{-4}$ systematic errors could prove very difficult to control.

We've made great strides, particularly in the past few years in revealing new manifestations of CP violation, but there is still a long way to go...



"I'll tell you what's beyond the observable universe -- lots and lots of unobservable universe."